What the parton cascade tells us about RHIC

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Workshop on "Collective flow and QGP properties"

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- based on projects with: P. Huovinen, Z. W. Lin, S. A. Voloshin, M. Gyulassy

Outline

- Covariant parton transport theory
  - transport equation & ingredients
- Elliptic flow (v_2) puzzle at RHIC
  - observation: large and saturating anisotropy $v_2(p_\perp)$
  - puzzle for models → large opacities?
- Looking for ways out
  - dynamics? - $2 \leftrightarrow 3$
  - hadronization? - parton coalescence
- Did we reach the hydro limit?

The theory

Covariant parton transport theory

Pang, Zhang, Gyulassy, D.M., Vance, Csizmadia, Pratt, Cheng, ...

Simplest Lorentz-covariant nonequilibrium dynamical framework

- dynamics governed by the mean free path: $\lambda(s,x) = 1/\sigma(s)n(x)$
  - interpolates between ideal hydro $\lambda = 0$ and free streaming $\lambda = \infty$
- natural decoupling, $\lambda(t \to \infty) \to \infty$ ↔ no need for sudden Cooper-Frye

Nonlinear 6+1D transport equation:

$$p^\mu \partial_\mu f_i(x,\vec{p}) = \overbrace{S_i(x,\vec{p})}^{\text{source}} + \overbrace{C_i^{el.}[f](x,\vec{p})}^{2 \to 2\ (\mathrm{ZPC},\mathrm{GCP},\ldots)} + \overbrace{C_i^{inel.}[f](x,\vec{p})}^{2 \leftrightarrow 3\ (\mathrm{MPC})} + \ldots$$

solvable numerically → only a few covariant algorithms: ZPC, MPC, Bjorken-τ, ...

Real dynamical parameter: transport opacity

[see NPA 697, 495 ('02)]

$$\chi \equiv \langle n_{coll}\rangle \sigma_{tr}/\sigma_{el} \quad \propto \quad \sigma_{tr} \times dN/d\eta$$

Three ingredients (for RHIC)

- initial conditions
  - soft + hard (minijets)
  - gluon saturation

  ...
- cross sections
  - e.g., perturbative QCD (LO) + screening

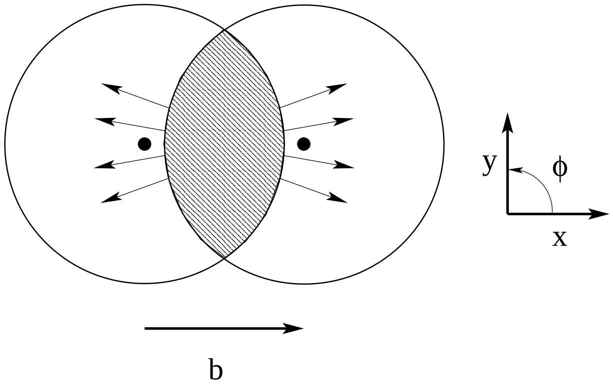
  ...
- hadronization
  - parton-hadron duality (1 parton → 1 pion)
  - independent jet fragmentation
  - Lund string model
  - parton coalescence

  ...

Applications - collective phenomena

Elliptic flow

- **momentum-space anisotropy of particle production in A+A collisions**

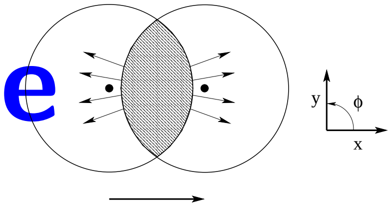


$$\frac{dN}{d\phi dX} \equiv \frac{1}{2\pi}\frac{dN}{dX}[1 + 2\sum_{n=1} v_n(X)\cos(n\phi)] \qquad \rightarrow \qquad v_2(X) \equiv \langle \cos 2\phi \rangle_X$$

X : **event and particle selection, e.g., centrality, transverse momentum**

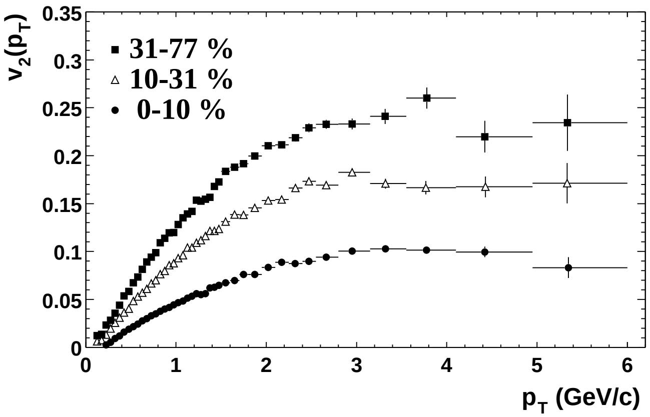
- **origin of $v_2 \neq 0$: coordinate-space anisotropy $(b > 0)$ & reinteractions**

RHIC elliptic flow puzzle

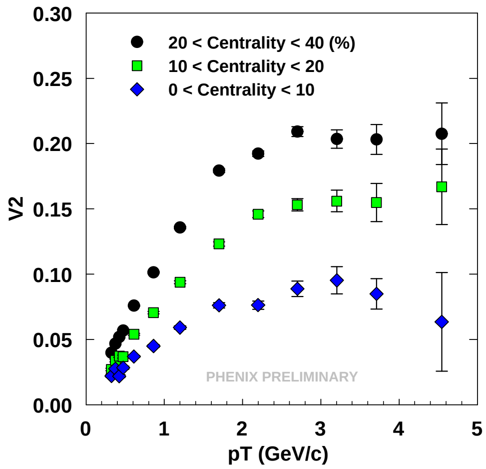


Experimental data vs. Theoretical expectations

STAR, PRL 90, 032301 ('03)



PHENIX, NPA715, 765 ('03)



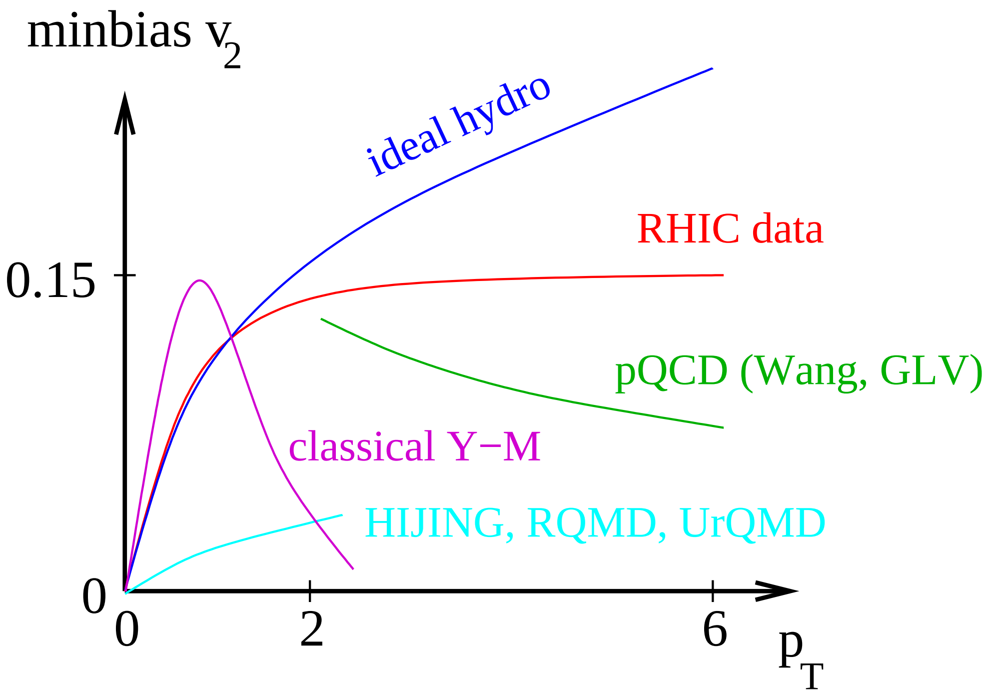
- **large and saturating anisotropy $v_2(p_\perp)$**

[Heinz, Kolb, Huovinen et al;

Gyulassy, Vitev, Wang et al;

Sorge et al; Bleicher, Stöcker et al;

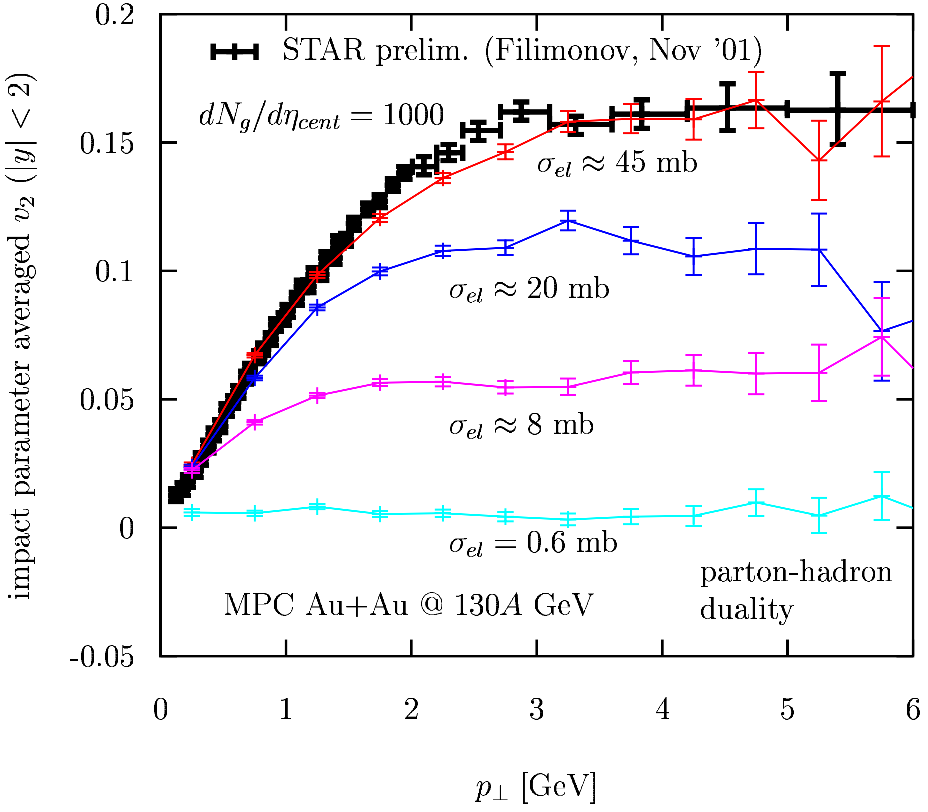
Krashnitz, Venugopalan et al]



- **difficult to explain**

$v_2(p_T)$ from parton transport

D.M. & Gyulassy, NPA 697 ('02):



covariant parton transport model **MPC 1.6.0** (D.M.)

$$p^\mu \partial_\mu f_i = S_i + C_i^{2\to 2}[f] + \ldots$$

- minijet initconds + gluon sat.
- screened 2 → 2 pQCD cross sections
- 1 parton → 1 pion hadronization

- **v_2 saturation pattern reproduced with $15\times$ enhanced opacities**

$$\sigma_{el} \times dN_g/d\eta \approx 45000 \text{ mb} \gg \text{pQCD } (3 \text{ mb} \times 1000)$$

Look for ways out

One bet: inelastic processes

- hope: opacity enhancement due to particle production

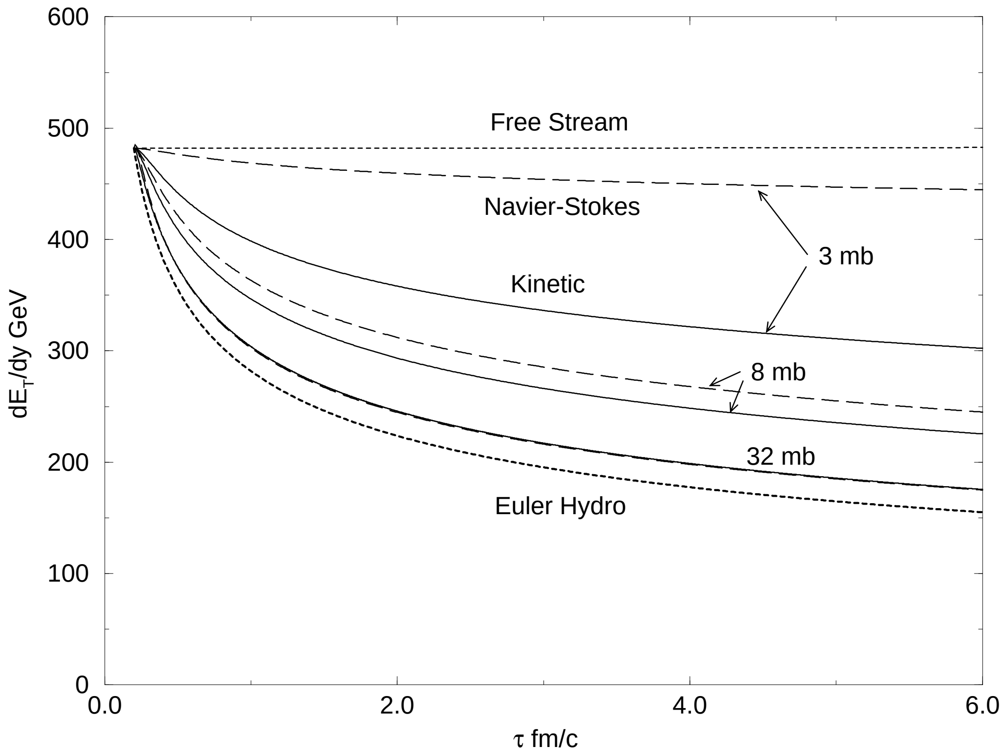
- natural step: investigate $2 \to 2$ + $2 \leftrightarrow 3$
  - algorithm for $3 \to 2$ has been developed (MPC)
  - but: several orders of magnitude larger CPU time required for covariance ($\ell^{-1/5}$)
  - unfortunately, full 3+1D simulation for RHIC is unfeasible

⇒ needed to get insight from a simpler problem (symmetry):

- choose: E_T evolution in 1+1D Bjorken scenario
  - expanding systems cool due to $p\,dV$ work
  - E_T reflects pdV work ⇒ measures strength of collective phenomena
  - e.g., ideal hydro:

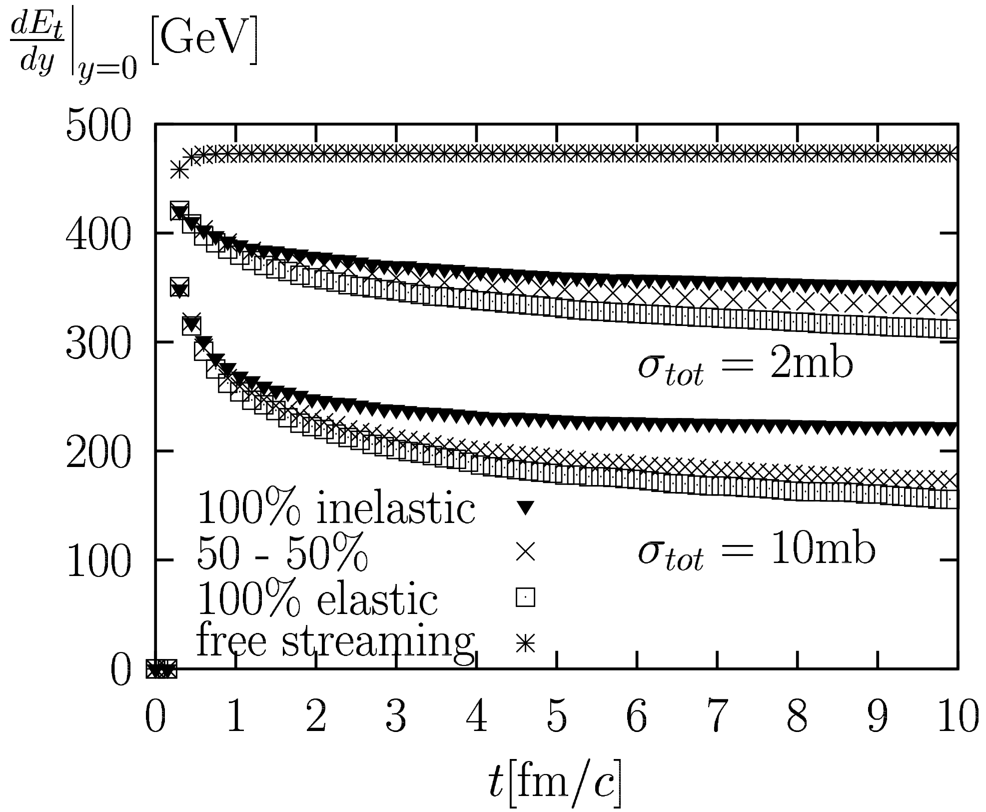
$$T \propto \tau^{-1/3} \qquad \Rightarrow \qquad dE_T/dy \propto \tau^{-1/3}$$

pure $2 \to 2$ (Zhang & Gyulassy):



- $p\,dV$ **work increases with opacity**
- **demonstrated approach to Navier-Stokes**

$2 \leftrightarrow 3$ vs $2 \to 2$ (D.M. & Gyulassy):



- **elastic and inelastic channels have similar transport effect**

$\Rightarrow$ **effect of $2 \leftrightarrow 3$ is roughly a doubling of $2 \to 2$ cross section**

Hope looks gone: **there is room for $2-3\times$ larger opacities** **but not** $15\times$

Another idea: parton coalescence

Biró et al, Lévai, Csizmadia, Ko, Lin, Hwa, Yang, Greco et al, Fries et al, D.M., Voloshin, ...

An alternative to $1 \to \text{many}$ independent fragmentation

- **picture:** - **coalescence of massive** **"dressed" valence quarks**
  - **no dynamical gluons**

- **basic equations:** $qq \to meson$, $qqq \to baryon$ $\qquad \text{many} \to 1$

$$E\frac{dN_M(\vec{p})}{d^3p} = \int \frac{d\sigma^\mu p_\mu}{(2\pi)^3} \int d^3q |\psi_{\vec{p}}(\vec{q})|^2 f_\alpha(\vec{p_\alpha}, x) f_\beta(\vec{p_\beta}, x)$$

$$E\frac{dN_B(\vec{p})}{d^3p} = \int \frac{d\sigma^\mu p_\mu}{(2\pi)^3} \int d^3q_1 d^3q_2 |\psi_{\vec{p}}(\vec{q}_1, \vec{q}_2)|^2 f_\alpha(\vec{p_\alpha}, x) f_\beta(\vec{p_\beta}, x) f_\gamma(\vec{p_\gamma}, x)$$

hadron yield $\qquad$ space-time $\qquad$ wave-fn. $\qquad$ quark distributions

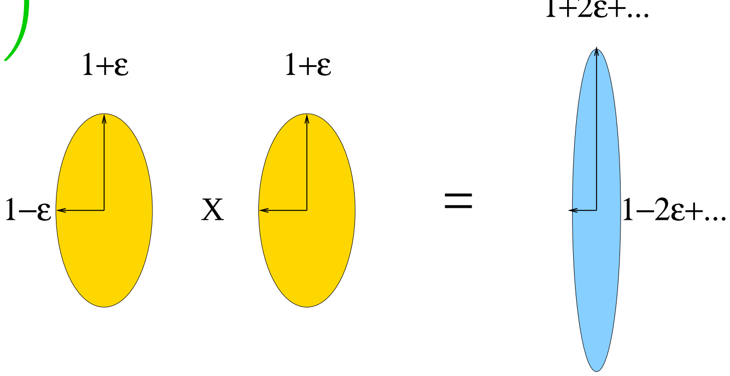
assumes: rare process, weak binding, factorizable 2-body and 3-body density matrix, smooth spacetime distributions, 3D hypersurface (sudden approx.)

- **can dominate over fragm. for $p_\perp < 4 - 5$ GeV**

Coalescence amplifies elliptic flow

[D.M & Voloshin, PRL 91 ('03)]

narrow wave fn. limit ($\vec{q} = 0$): $\quad \frac{dN_M}{d\phi} \propto \left(\frac{dN_q}{d\phi}\right)^2$



$$v_2^M(p_\perp) \approx v_2^a\left(\frac{p_\perp}{2}\right) + v_2^{\bar{a}}\left(\frac{p_\perp}{2}\right)$$
$$v_2^B(p_\perp) \approx v_2^a\left(\frac{p_\perp}{3}\right) + v_2^b\left(\frac{p_\perp}{3}\right) + v_2^c\left(\frac{p_\perp}{3}\right)$$

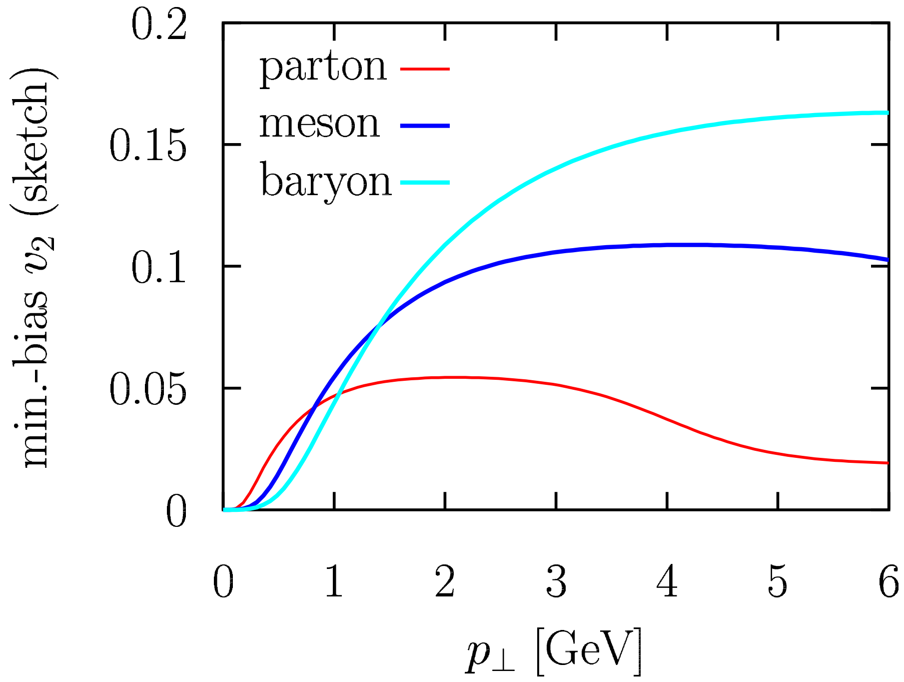
$\Rightarrow$ **hadron flow amplified at high $p_\perp$**

if all quarks have same v_2:

$3\times$ **for baryons**

$2\times$ **for mesons**

" $v_2^h(p_\perp) \approx n \times v_2^q(p_\perp/n)$ "



- **this KEY EFFECT solves opacity puzzle (much smaller parton v_2 needed)**

Solution to opacity puzzle

1) elliptic flow amplification $\Rightarrow$ $2-3\times$ **smaller parton v_2 is enough**

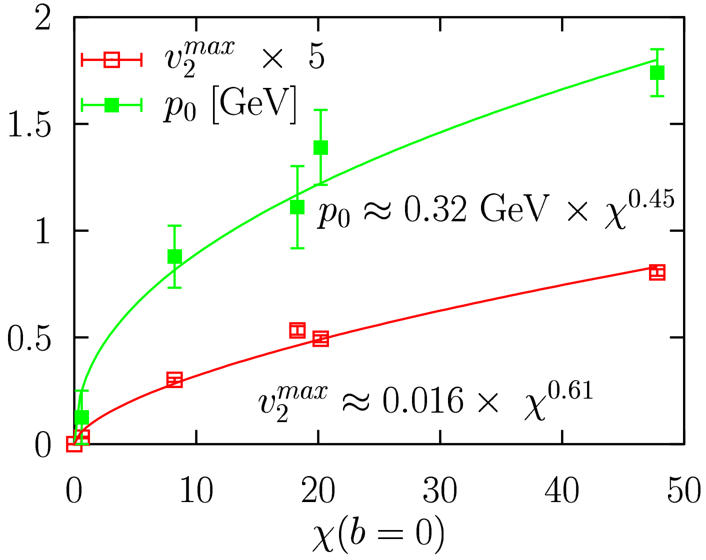
weaker than linear opacity dependence

$$v_2^{max}(\chi) \propto \chi^{0.61}$$

$$v_2^{parton}(p_\perp, \chi) \approx v_2^{max}(\chi)\tanh(p_\perp/p_0(\chi))$$

$\Rightarrow$ $3-6\times$ **opacity reduction** $[\chi \sim \sigma \times dN/d\eta]$
[lower(upper) value for purely mesons(baryons)]

[D.M & Gyulassy, NPA 697, 495 ('02)]



2) $15-20$**% nonflow correlations in first v_2 data** $\Rightarrow$ 25% **opacity reduction**

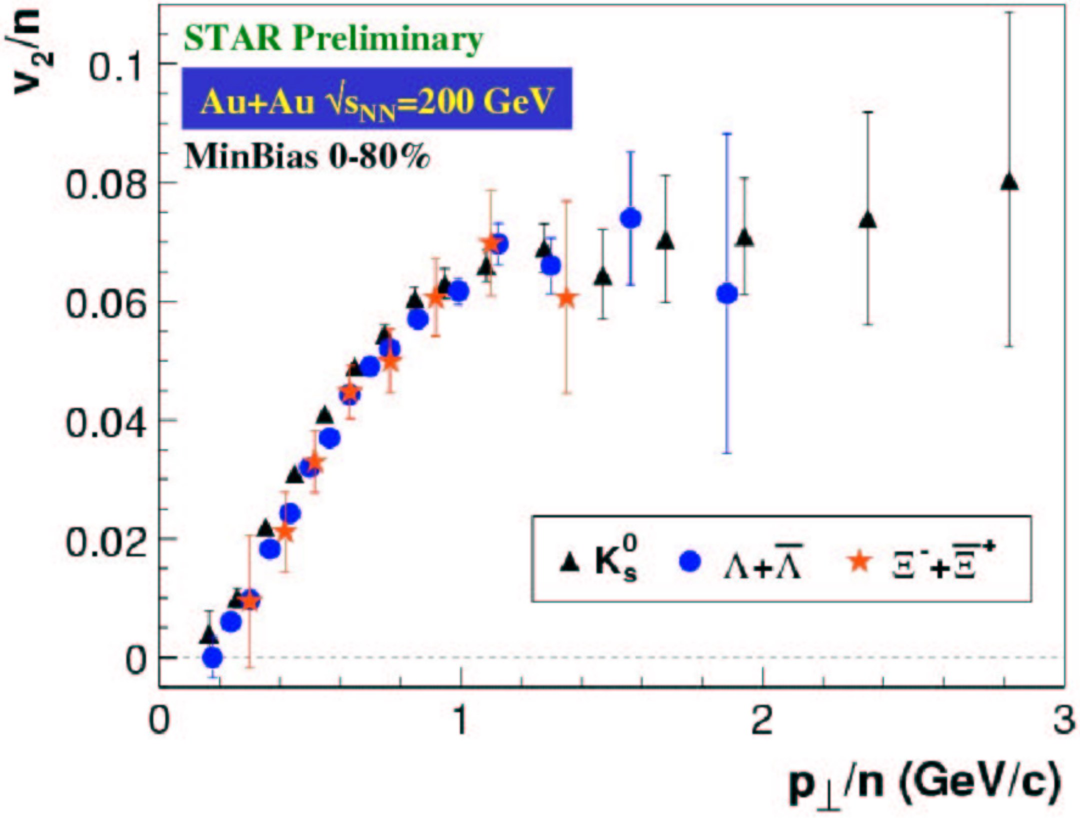
3) theoretical uncertainties $\Rightarrow$ **factor $2-3$ in opacity** [D.M & Gyulassy, NPA 661]
inelastic processes (e.g., $2 \leftrightarrow 3$), cross sections, initial parton density, ...

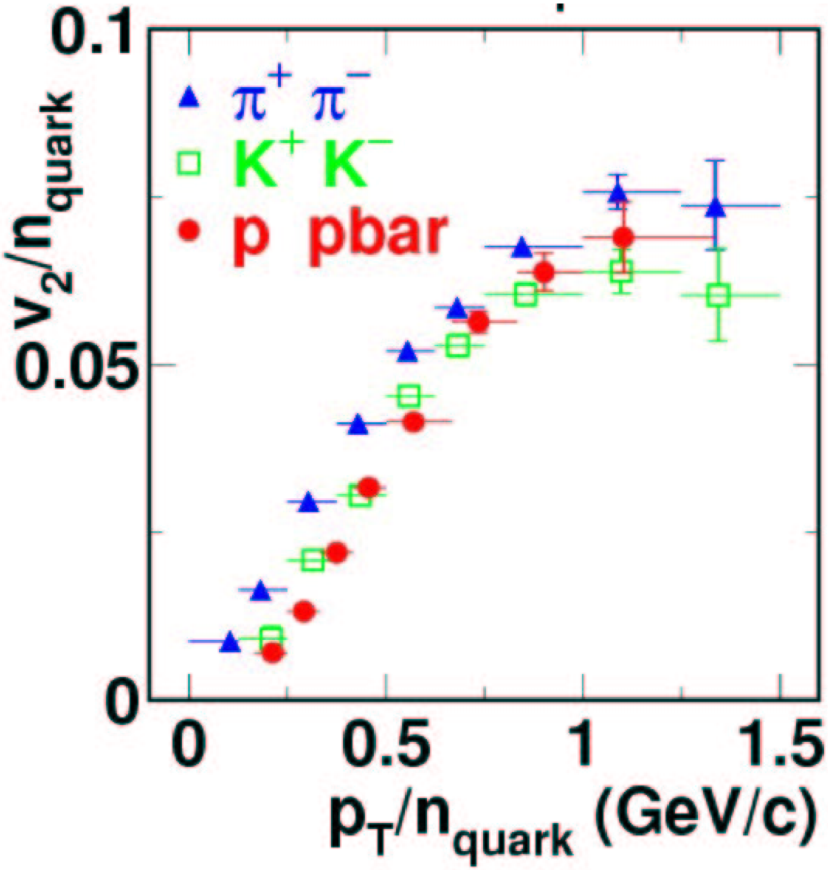
$\Rightarrow$ **factor 15 within reach**

Success of flow scaling predictions

Sorensen [STAR], nucl-ex/0305008: K_0^S, Λ
Castillo [STAR] at HIC03: Ξ

PHENIX, nucl-ex/0305013: π, K, p





- **coalescence predictions confirmed for $\pi, K, K_0, p, \Lambda, \Xi$ → yet to see Ω, ϕ**
- **interestingly, RHIC data indicate $v_2^q \approx v_2^s$**

Story is not over...

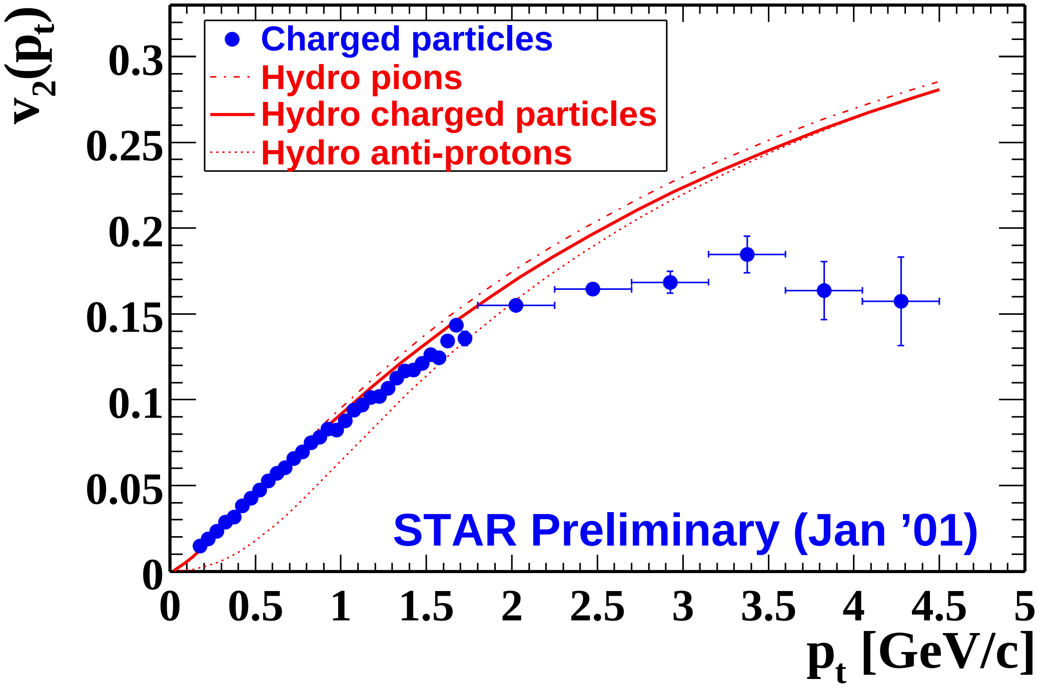
Further progress on all fronts possible/necessary

- inelastic channels
  - would love to see full 3+1D RHIC simulations one day
- coalescence (hadronization)
  - promising (also meson/baryon ratios) but treatment is oversimplified
  - check other observables
- initial conditions?
  - much better control desired
- dynamics?
  - critical scattering? strongly coupled regime?
  - correlation dominated limit ($\cancel{f}$)? - virtually unexplored
  - field/wave limit? 3+1D classical Yang-Mills?
  - or maybe all is hydro?

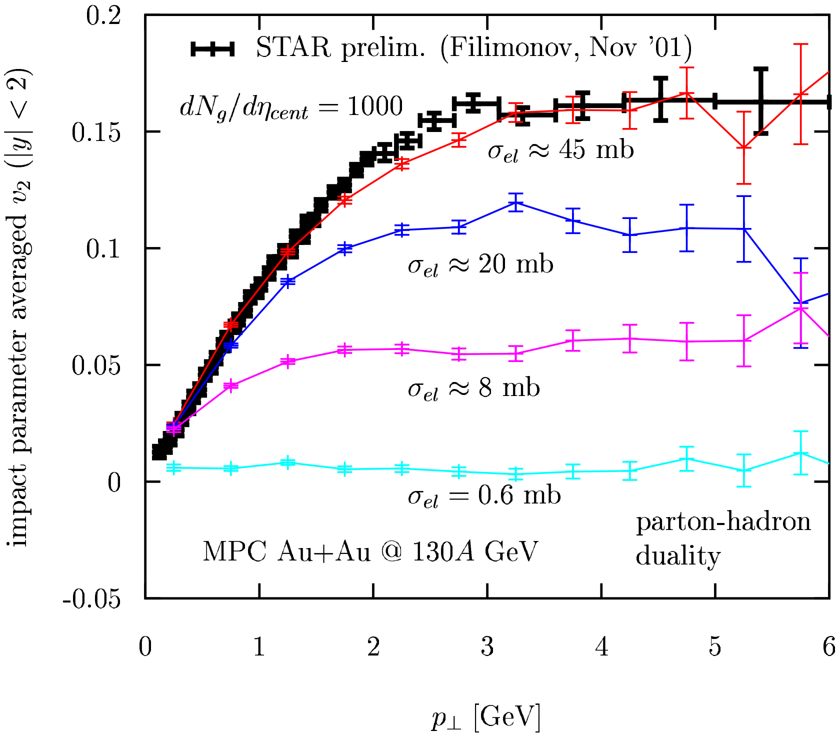
Did the transport results prove hydro?

Many think yes. BUT let's see...

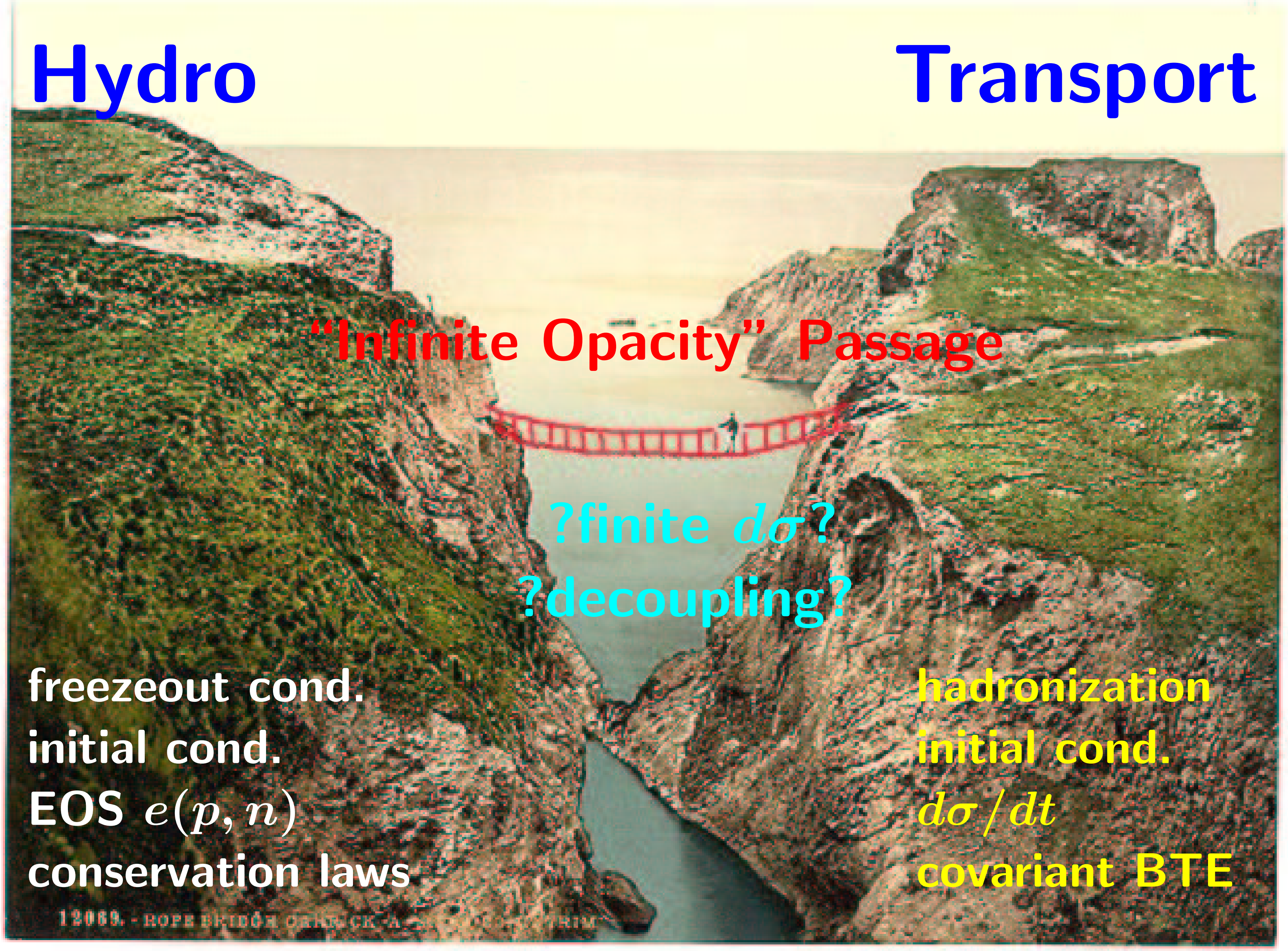
ideal hydro (Kolb, Heinz, Snellings) **transport**



$\overset{?}{=}$



$\Rightarrow$ **so, extreme 15x perturbative opacities justify hydro?**



Hydro	Transport
freezeout cond.	hadronization
initial cond.	initial cond.
EOS $e(p, n)$	$d\sigma/dt$
conservation laws	covariant BTE

"Infinite Opacity" Passage

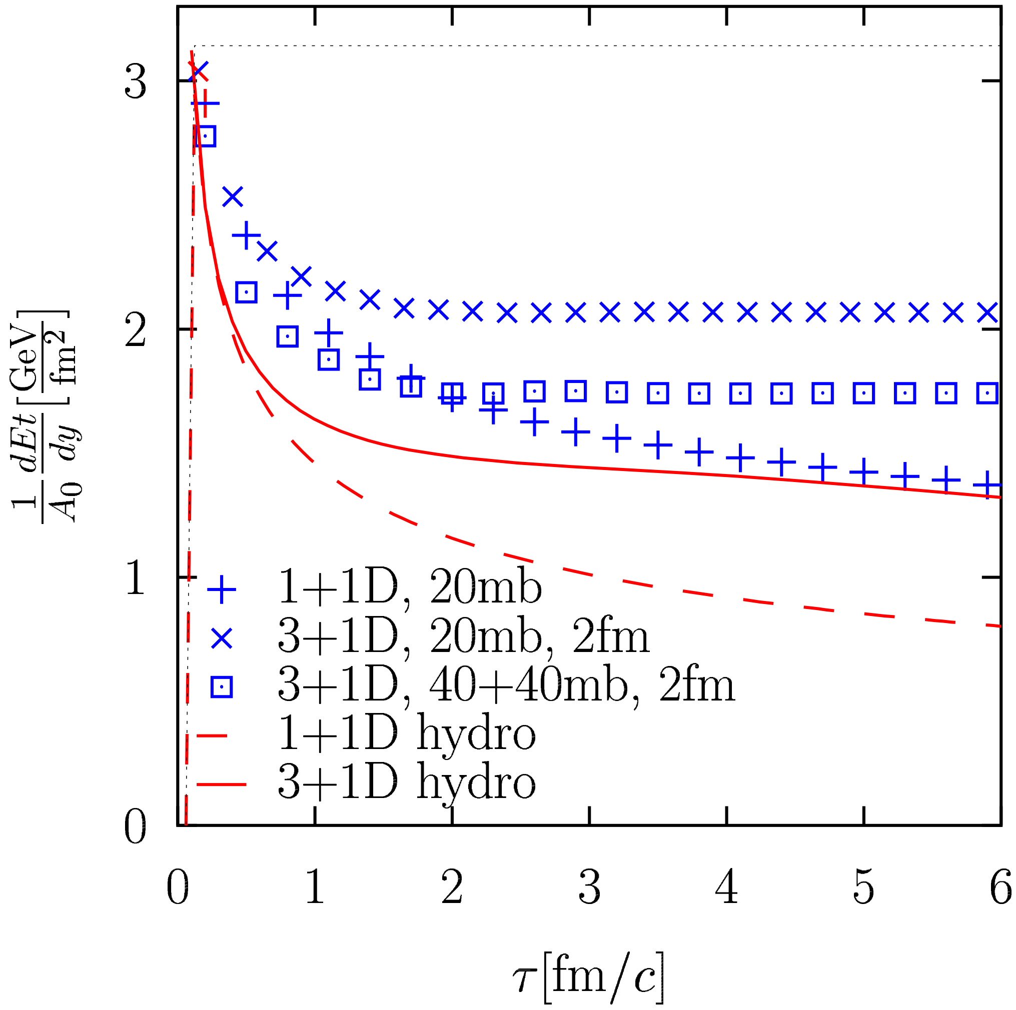
?finite $d\sigma$?

?decoupling?

One precursor: E_T work

Gyulassy,Zhang,D.M.

MPC vs hydro (1+1D and 3+1D) PRC 62, 054907 ('00)



← free streaming ($\sigma = 0$)

← pQCD ×4 with $R = 2$ fm

← pQCD ×20 with $R = 2$ fm

← pQCD ×4 with $R = \infty$

hydro with $R = 2$ fm

← hydro with $R = \infty$

- **ideal hydro** (code: Rischke & Dumitru) **does more work than transport**

⇒ **even** 20× **pQCD opacities found insufficient to maintain equilibrium**

How can both get the v_2 data then?

Key: different initial conditions & thermodynamics

hydro:

- $\tau_0 = \tau_{th} = 0.6$ **fm/**c
- **QGP-in-bag + hadron gas EOS**
- **wounded nucleon entropy profile**
- **freezeout at** $T_{FO} \approx 120$ **MeV**

parton transport:

- $\tau_0 = \tau_{form} = 0.1$ **fm/**c
- **massless gas (**$e = 3p$**, if in thermal equil.)**
- **binary collision density profile**

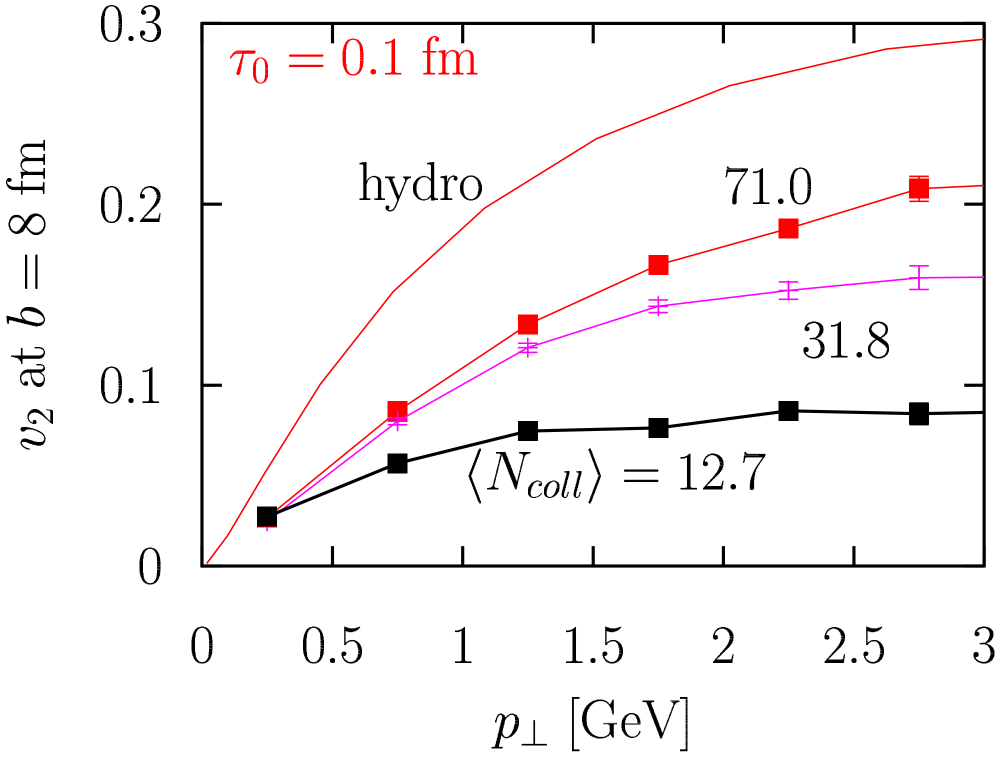
⇒ **apples to oranges comparison...**

Apples-to-apples elliptic flow

Take same hydro and transport initconds & EOS, with $\tau_0 = 0.1$ fm/c

($T_0 = 700$ MeV, binary coll. profile, $e = 3p$, $b = 8$ fm, $dN/d\eta(b = 0) = 1000$, $T_{FO} = 120$ MeV)

D.M. & Huovinen ('03):



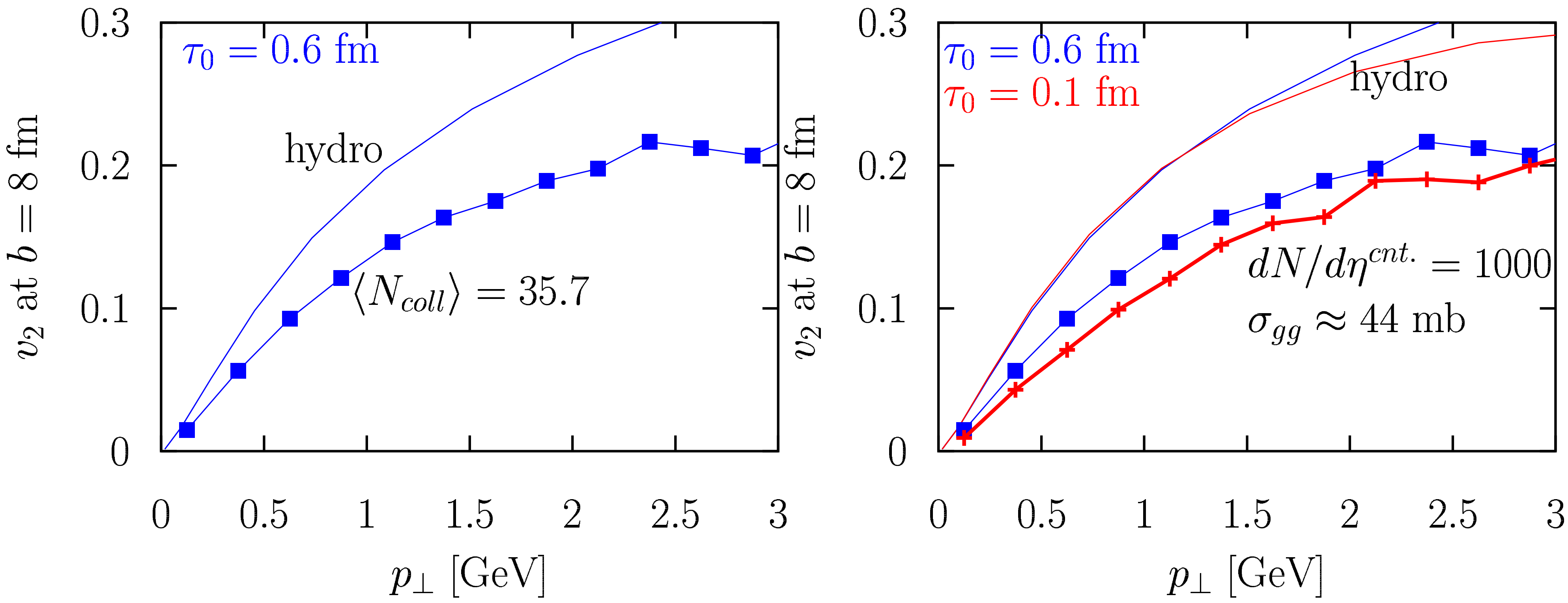
⇒ **large dissipation, transport v_2 is 30-50% reduced relative to hydro**

→ $N_{coll} \gg 3$, **still not thermal - because of rapid longitudinal expansion**

Apples-to-apples elliptic flow (2)

Now same hydro and transport initconds but $\tau_0 = 0.6$ fm$/c$, scaled $T_0 \sim \tau_0^{-1/3}$

D.M. & Huovinen ('03):



$\Rightarrow$ **large dissipation, transport v_2 is 30-50% reduced relative to hydro**

$\Rightarrow$ **remarkably little sensitivity to initial time**

Extremely interesting

- **hydro:**
  - remarkable insensitivity to initial time → are QGP EOS results robust, too?
  - is it an accident? or, can it be due to common freezeout temperature?
  - any analytic understanding possible?

- **transport:**
  - counter-intuitive: fewer collisions but same flow?

$$\langle n_{coll}\rangle = \int dt \frac{d\sigma_{el}}{dt} \int dz \rho \left(\vec{x}_0 + z\hat{\mathbf{n}}, \tau = \frac{z}{c}\right) \approx \frac{dN}{dy} \frac{\sigma_{el}}{2\pi R_G^2} \log \frac{R_G}{\tau_0}$$

  - on the other hand:

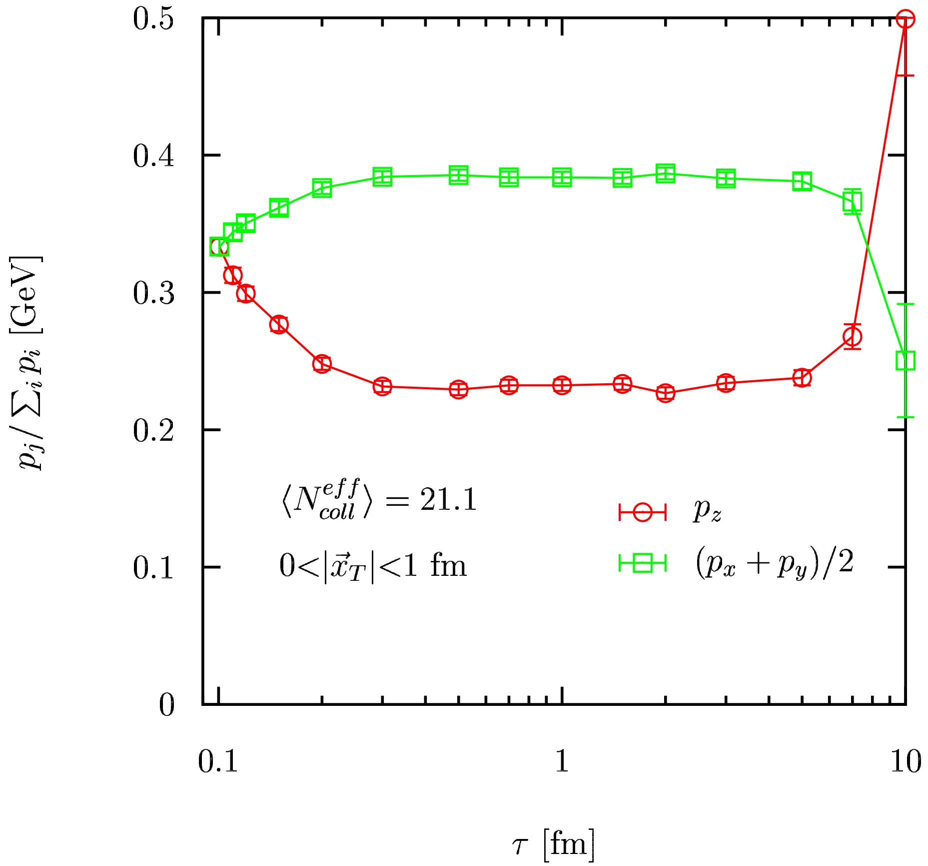
$$\Gamma_{coll} \propto n\sigma \propto 1/\tau, \qquad \Gamma_{exp} \propto 1/\tau \quad \Rightarrow \quad \Gamma_{coll}/\Gamma_{exp} \sim const$$

  - also only one scale [NPA 697, 495] R/τ_0 changes, while $\sigma dN/d\eta$, μ/T_0 stay same

In either case, 44 mb is insufficient for hydro limit → need even larger.

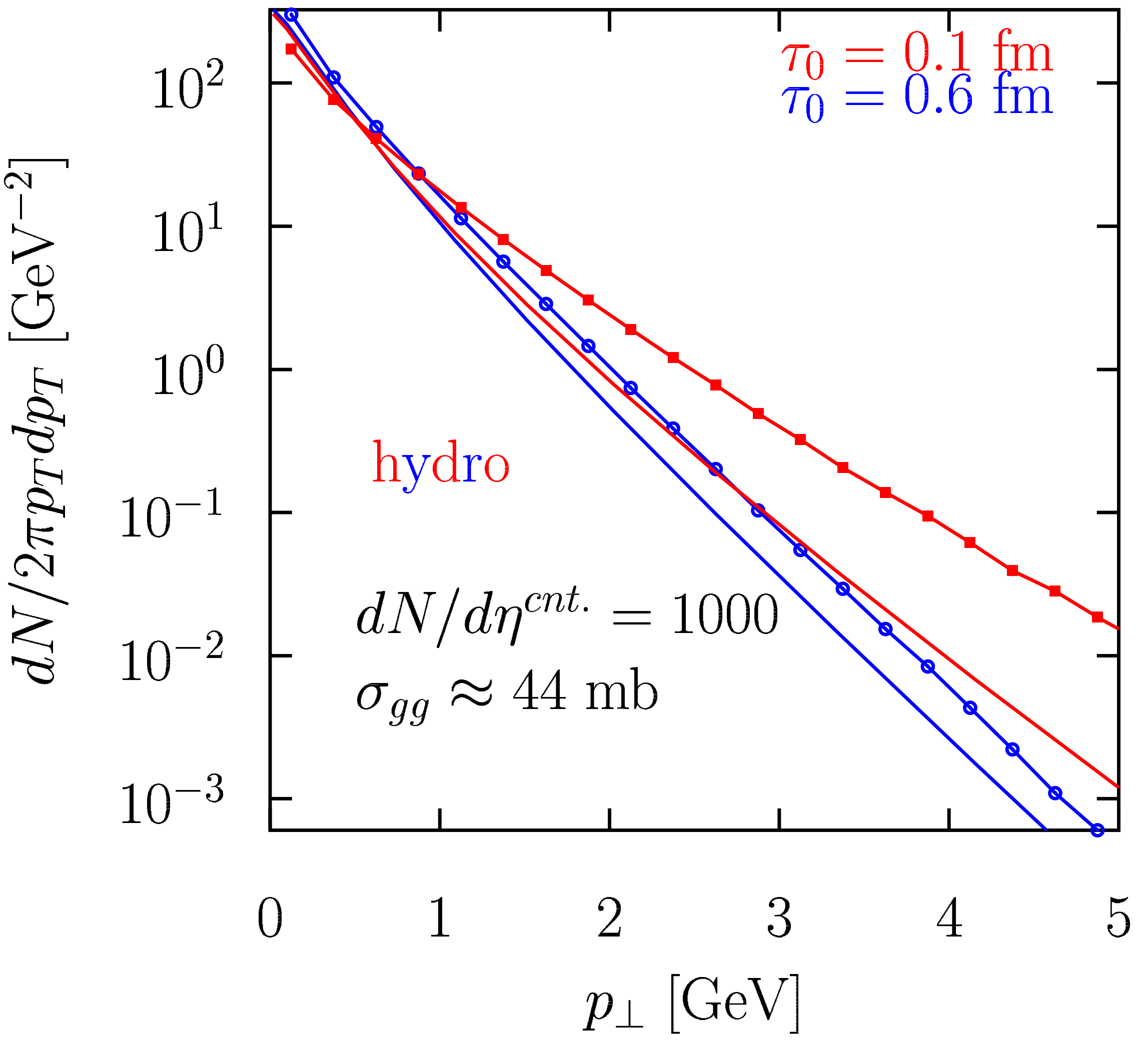
Pressure anisotropy

Study pressure tensor $b = 0$, $\tau_0 = 0.1$ fm, (same minijet initial conditions)



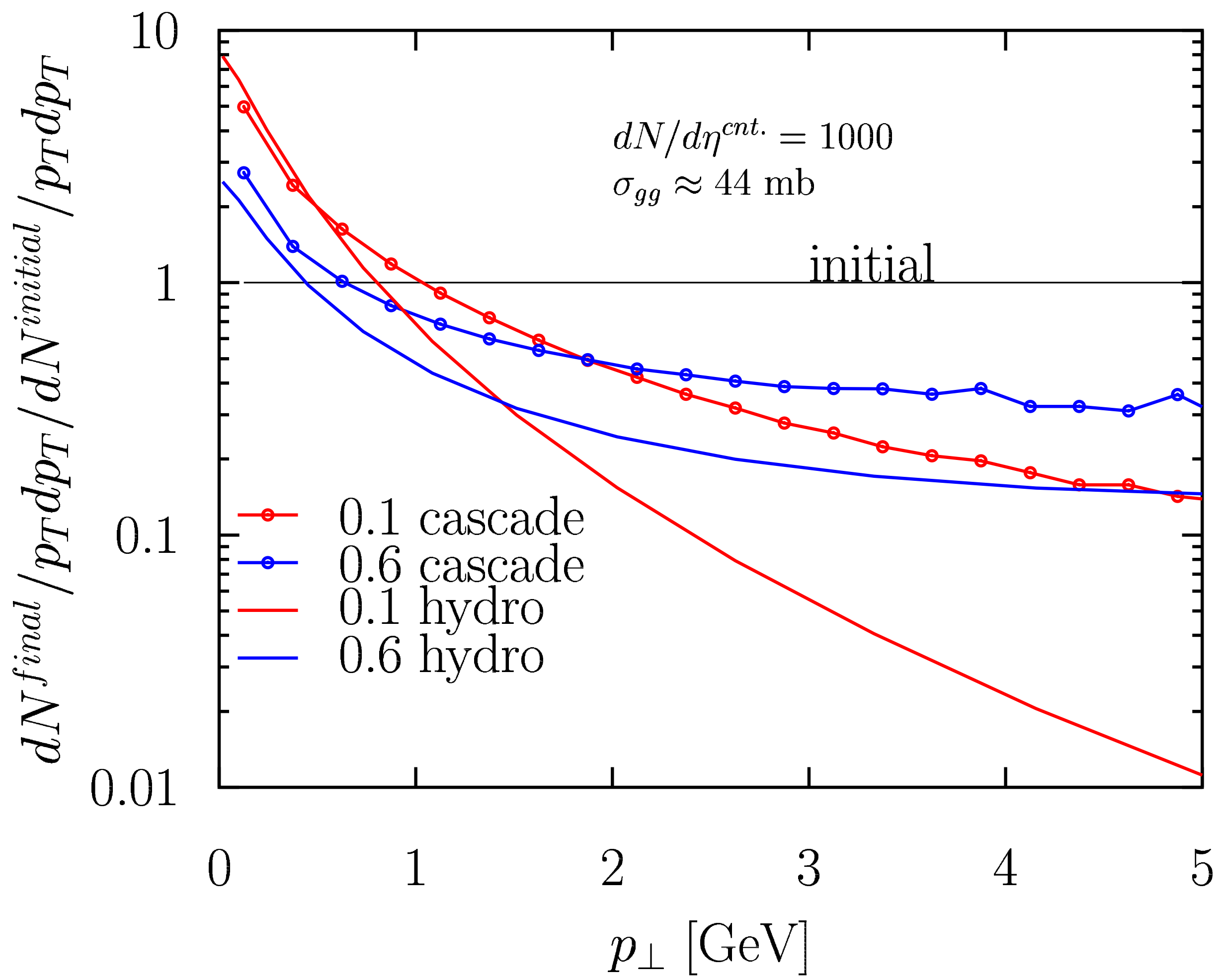
- **even in center, large pressure anisotropy $p_{trans} \sim 2p_z$**
- **evolution rapidly departs from hydro limit → some anisotropic hydro?**

Final spectra



- **transport spectra strongly depend on $\tau_0 \rightarrow$ can one pinpoint form. time?**
- **hydro spectra are less sensitive, and agree below $p_T < 1$ GeV**

Quenching (final/initial)



- **relative quenching weakens in transport for larger τ_0**

$\Rightarrow$ **maybe a larger $\tau_0 > 1$ fm can save v_2 vs quenching puzzle?**

Conclusions

- **What we learned:**
  - large v_2 at RHIC indicates at least pQCD opacities (and possibly much larger)
  - absolutely amazing why hydro works - even 45mb is not enough
  - hydro and transport v_2 seem robust against initial τ_0 (much less so for spectra)

- **Open issues (my incomplete list):**
  - map out initial conditions - e.g., formation time?, initial condition models?
  - better understanding of microscopic dynamics
    develop and test various dynamical models/limits, make codes available (OSCAR)
    3+1D inelastic transport, viscous hydro, 3+1D ideal hydro, 3+1D Yang-Mills,
    strongly coupled, highly-correlated systems, ...
  - refine/further test hadronization models - e.g., parton coalescence
  - $dE_T/dN(b) = const$ puzzle
  - v_2 vs quenching puzzle
  - high-p_T angular correlations (flow vs jets)
  - HBT puzzle